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Using Artificial Seagrass for Promoting Positive Feedback Mechanisms in Seagrass Restoration

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Worldwide, seagrass meadows are under threat. Consequently, there is a strong need for seagrass restoration to guarantee the provision of related ecosystem services such as nutrient cycling, carbon sequestration and habitat provision. Seagrass often grows in vast meadows in which the presence of seagrass itself leads to a reduction of hydrodynamic energy. By modifying the environment, seagrass thus serves as foundation species and ecosystem engineer improving habitat quality for itself and other species as well as positively affecting its own fitness. On the downside, this positive feedback mechanism can render natural recovery of vanished and destroyed seagrass meadows impossible. An innovative approach to promote positive feedback mechanisms in seagrass restoration is to create an artificial seagrass (ASG) that mimics the facilitation function of natural seagrass. ASG could provide a window of opportunity with respect to suitable hydrodynamic and light conditions as well as sediment stabilization to allow natural seagrass to re-establish. Here, we give an overview of challenges and open questions for the application of ASG to promote seagrass restoration based on experimental studies and restoration trials and we propose a general approach for the design of an ASG produced from biodegradable materials. Considering positive feedback mechanisms is crucial to support restoration attempts. ASG provides promising benefits when habitat conditions are too harsh for seagrass meadows to re-establish themselves.

Keywords: artificial seagrass, ecosystem restoration, seagrass sediment light feedback, positive feedback mechanisms, biodegradable

INTRODUCTION

Seagrass meadows provide important ecosystem services (Waycott et al., 2009; Reynolds et al., 2016) such as nutrient cycling (McGlathery et al., 2007), carbon sequestration (Duarte et al., 2004), habitat provision (Orth et al., 2006) and the resulting support of biodiversity (Hemminga and Duarte, 2000) and fisheries (Beck et al., 2001). By modifying the environment, seagrass serves as foundation species and ecosystem engineer improving habitat quality for other species as well as positively affecting its own fitness (van der Heide et al., 2011). Moreover, seagrass plays an indirect, but important role in coastal protection by the absorption of wave energy (Paul and Amos, 2011) and the stabilization of sediment (Christianen et al., 2013). Even though the services of seagrass meadows have been widely recognized, these ecosystems are under threat and a global decline has been observed over the last decades (Lotze et al., 2006; Short et al., 2011). Since the 1980s, seagrass decrease in many European areas has slowed and even reversed thanks to changes in management and regulations allowing for natural (re)colonization (de los Santos et al., 2019). However, with a decline of 7% per year toward the end of the twentieth century (Waycott et al., 2009), seagrass beds still rank among the most threatened ecosystems on Earth.

Threats for Seagrass Meadows

The reasons for the worldwide decline of seagrass meadows are manifold and include diseases, natural and anthropogenic disturbances as well as eutrophication (Orth et al., 2006). A major driver of seagrass loss was a pandemic caused by the slime-mold *Labyrinthula zosterae*, commonly known as the wasting disease that dramatically reduced *Zostera marina* stands in the 1930s (Cotton, 1933) and totally wiped out the subtidal *Z. marina* in the North Atlantic (Dolch et al., 2013). Natural disturbances can lead to reduced seagrass growth or even a total loss of seagrass ecosystems (van Katwijk et al., 2016). Erosion, for instance, can lead to scouring around shoots and result in their dislodgment by hydrodynamic forces (Infantes et al., 2011). Erosion processes also result in highly turbid water reducing light availability for photosynthesis. Small or short term reductions in light availability may cause reversible stress (Collier et al., 2012), but minimum light requirements are often not met after vegetation cover has been lost. Another natural disturbance in seagrass meadows can be the burial of young plants as it has a significant impact on growth and survivorship. Burial can be caused by natural dune migration and bioturbation, but also by the settlement of suspended material as a result of reduced flow velocities (Cabaço et al., 2008). In addition to natural threats, seagrass is exposed to anthropogenic impacts that can lead to the destruction and loss of seagrass meadows. These disturbances include mechanical destruction by anchoring vessels that can uproot seagrass in large areas (Abadie et al., 2016) as well as stress and damage by underwater construction works like dredging or shore nourishment campaigns that lead to enhanced turbidity. Another major anthropogenic impact on coastal waters is the intake of nutrients and chemicals (e.g., herbicides) through input by rivers or sewage (Vitousek et al., 1997) directly affecting seagrass health due to ammonium toxicity and nitrate inhibition through internal carbon limitation (Burkholder et al., 2007). Eutrophication also indirectly affects seagrass health as higher nutrient levels promote growth of phytoplankton, epiphytes, and macroalgae leading to increased turbidity and shading of seagrass plants (Burkholder et al., 2007). These anthropogenic impacts are considered the major drivers of global seagrass loss (Duarte et al., 2004) and as long as they persist, seagrass restoration will continue to be deemed unsuccessful (van Katwijk et al., 2009).

Recovery of Seagrass Meadows

By reducing hydrodynamic energy, seagrass meadows promote the settling of suspended sediment particles (Bouma et al., 2005), improving water clarity and quality (Short et al., 2007). Moreover, the root and rhizome system stabilizes the trapped sediment even when aboveground biomass is low (Barbier et al., 2011). This positive feedback between seagrass and sediment suspension/deposition is called the seagrass sediment-light (SSL) feedback (Adams et al., 2016). While this feedback has a self-facilitative effect in intact seagrass meadows, it can also lead to bistability (Wilson and Agnew, 1992; Scheffer et al., 2009) with two alternative stable states: (i) a seagrass meadow with relatively clear water, and (ii) bare sediment beds with turbid water (van der Heide et al., 2007). Non-linearities in the response to environmental drivers can lead such bistable systems to abruptly shift from one state into another by only small environmental changes (Carr et al., 2016). The resilience of bistable systems is low, meaning that after a disturbance with a consequential system shift, the systems cannot return easily into their previous state due to hysteresis even if the disturbance has been eliminated (Scheffer et al., 2001). In exposed locations, the SSL feedback-induced bistability (Carr et al., 2010) can render the natural recovery of seagrass meadows impossible. Prolonged high turbidity, for example, prevented the recovery of *Z. marina* in the Greifswalder Bodden in the Baltic Sea despite reductions in nutrient inputs over 15 years (Munkes, 2005).

Around the globe, many restoration projects try to re-establish seagrass meadows, and many research projects have been dedicated to this aim (Paling et al., 2009; van Katwijk et al., 2016). A range of restoration guidelines combine the lessons learned from past restoration efforts (e.g., Campbell, 2002; Ganassin and Gibbs, 2008; Moksnes et al., 2016; van Katwijk et al., 2016). They all identify a variety of reasons for the failure of the numerous restoration activities in the past, one of the main being that the selected site does not provide the required conditions for seagrass establishment (van Katwijk et al., 2016). For example, high water and sediment movement at exposed sites are acknowledged to be impedimental to transplant survival (Campbell, 2000). Hence, low-energy areas are recommended for restoration schemes to improve restoration success rates (Orth et al., 1994). However, providing the right shelter, restored seagrass can thrive in high-energy environments. Established beds of seagrass in high velocity environments probably developed in adjacent low-energy areas or during calm periods and expanded once they were well established (Koch, 2001). At sites with high hydrodynamic energy, habitat enhancement strategies that promote positive feedback mechanisms can thus increase restoration success. Therefore, we propose creating an artificial seagrass (ASG) that mimics the SSL function of natural seagrass. Such ASG provides a window of opportunity with respect to suitable hydrodynamic and light conditions as well as sediment stabilization to allow natural seagrass to either grow from seeds, take root after transplantation or expand existing meadows more easily. Here, we provide an overview of challenges and open questions when it comes to the application of ASG for promoting seagrass restoration. We first summarize existing restoration programs that deal with the challenges in seagrass restoration by promoting positive feedback mechanisms (section 2) and subsequently outline the open questions associated with the planning and application of artificial seagrass for restoration purposes (section "Proposed Approaches for Seagrass Restoration With ASG").

State-of-the-Art in Seagrass Restoration

Restoration efforts provide a conceivable way to support the recolonization process and promote seagrass regrowth. A decisive role in seagrass restoration is played by the self-facilitative effect resulting from the seagrass sediment-light (SSL) feedback (Maxwell et al., 2017). Crossing a minimum threshold of reintroduced individuals and a minimum size of the transplantation area seem to be necessary to reduce turbidity from adjacent bare areas (van der Heide et al., 2007) and thus increase survival and population growth rate of transplanted seagrass plants or seeds (van Katwijk et al., 2016). However, large-scale transplantations are in most cases not feasible, so that restoration may only be possible if clarity of the water column in a dedicated area is provided by other means, e.g., by the shelter of other species such as mussel beds (Bos and van Katwijk, 2007).

Promoting Positive Feedback Mechanisms by the Use of Artificial Structures

If natural protection structures are not present and cannot be introduced at the selected restoration site, alternative solutions and innovative approaches such as enclosures or ASG become necessary (van der Heide et al., 2007; **Table 1**). Artificial structures promoting positive feedback mechanisms provide promising benefits for the restoration of natural seagrass by preventing transplants to be dislodged by waves, currents and foraging fauna (Campbell and Paling, 2003). They can either directly anchor the transplanted seedlings or stabilize the sediment surrounding the transplantation (e.g., Short et al., 2002; Park and Lee, 2007; Leschen et al., 2010).

Numerous laboratory studies utilizing ASG to investigate the impact of submerged vegetation on the hydrodynamic regime (e.g., Nepf and Vivoni, 2000; Bouma et al., 2005) show that, by providing the sheltering capacity that is typically attributed to natural seagrass meadows, ASG mats, consisting of several leaves fixed to a base layer and thus mimicking a meadow section are an innovative approach to promote positive feedback mechanisms. Villanueva et al. (2021) tested the extent of shelter behind ASG patches of different lengths and found that even with a highly flexible ASG, a length of 1 m parallel to flow direction provides shelter. ASG mats could thus potentially help to restore seagrass even under harsh conditions (high flow velocities and turbidity), where natural protection structures such as mussel beds are not feasible or where other restoration techniques have previously failed (Talbot and Wilkinson, 2000). Ideally, this concept could substitute current state-of-the-art labor and cost intensive measures such as anchors on single shoots or weighted frames.

Seagrass-like artificial structures have the advantage that they integrate into the environment and use the well documented natural feedback mechanisms to provide shelter (Adams et al., 2016). So far, ASG has mainly been used in other contexts, e.g., in offshore engineering, where it has found a commercial application in scour protection around pipelines, monopiles, and jackets, as it can significantly reduce flow and stabilize the sediment (Byers et al., 2006).

In a restoration context, artificial seagrass was applied to increase the long-term survivorship of *Cymodocea nodosa* seedlings by decreasing herbivory-induced mortality (Tuya et al., 2017). For this purpose, green plastic raffia "leaves" were attached around seagrass restoration plots. Although this was not the main interest of their research, the authors stated that the ASG probably modified small-scale hydrodynamics around the plots and thus reduced sediment transport. In a restoration experiment in Australia, ASG mats stabilized the sediment composition for transplants with significantly higher transplant survival and larger rhizome extension (Campbell and Paling, 2003). In another restoration test with ASG, *Zostera muelleri* cover in intertidal plots with seagrass transplanted into ASG mats decreased after 24 months, presumably because of the strong shading caused by the ASG leaves (Matheson et al., 2017). A flume experiment showed that the use of ASG can significantly reduce wave height, as well as current velocity (Carus et al., 2020) and thereby raise the input current velocity threshold which transplanted *Z. marina* shoots are able to withstand. In the past, the material used for the construction of ASG was always conventional plastic constituting an additional source of contamination (Andrady, 2011). Plastic gets brittle and transforms into microplastic, which may in turn absorb organic pollutants and be consumed by marine organisms (Cole et al., 2011). The ASG mats described above were produced from durable materials intended to stay in place long-term, which makes them unsuitable for restoration efforts that seek to re-establish natural vegetated ecosystems. The aim of all habitat enhancement should be to improve environmental conditions during the establishment only to the point where the seagrass meadow itself can provide these ecosystem-engineering functions.

PROPOSED APPROACHES FOR SEAGRASS RESTORATION WITH ARTIFICIAL SEAGRASS (ASG)

Prototype Design

The biggest challenge in seagrass restoration with ASG is to design a prototype that helps to overcome existing natural disturbances by providing the necessary shelter for re-growing seagrass while at the same time not causing any negative impact on the environment. Prototype design should comprise the design of the ASG leaves (e.g., material, buoyancy, stiffness, geometry) for the optimal reduction of hydrodynamic forces (Vogel, 1981). While it is certainly appealing to design the ASG to mimic the exact properties of natural seagrass, it is of high importance to optimize the design to more effectively

TABLE 1 | Overview of existing restoration trials using artificial structures.

Species	Facilitation structure	Plant material	Success (yes/no)	Probable reason for failure	Drawback	References
Potamogeton perfoliatus Stuckenia pectinata	Natural beds of *Ruppia maritima*	Shoots	Depending on scale of restoration	Shading effect	Not universally present	Hengst et al., 2010
Zostera marina	Natural mussel beds (*Mytilus edulis*)	Seedlings	Yes	–	Not universally present	Bos and van Katwijk, 2007
Amphibolis griffithii Posidonia sinuosa	Plastic garden mesh	Plugs	Yes	–	Plastic introduction	van Keulen et al., 2003
Amphibolis Antarctica	Sand filled hessian bags	None *	Yes	–	Species-specific	Irving et al., 2010
Zostera marina	Sand filled hessian bags	Seeds	Yes	–	Low germination rate of seeds	Unsworth et al., 2019
Zostera marina	Planting frames	Shoots	Yes	–	High losses if not thoroughly anchored, disturbance caused by the removal of the frames	Short et al., 2002; Leschen et al., 2010; Park and Lee, 2007
Zostera marina	Biodegradable grids	Shoots	Yes	–	High losses if not thoroughly anchored	Kidder et al., 2013
Zostera marina	Holes drilled into shells	Shoots	Yes	–	Relatively time-consuming	Lee and Park, 2008
Phyllospadix japonicas	Underwater structure built of cement, sand and water	Shoots	Yes	–	Underwater structure stays in place	Park and Lee, 2010
Cymodocea nodosa	ASG to decrease herbivory-induced mortality	Seedlings	Yes	–	Plastic introduction	Tuya et al., 2017
Posidonia australis	ASG with plastic leaves	Plugs	No	Storm damage	Plastic introduction	Campbell and Paling, 2003
Zostera muelleri	ASG with plastic leaves	Shoots	No	Shading effect, damage by wavering ASG leaves	Plastic introduction colonization of ASG with epifauna and flora	Matheson et al., 2017

**Recruitment of existing seedlings.*

provide shelter without shading the regrowing seagrass too much (by e.g., modifications on the material mechanical properties or the geometry).

The selection of a suitable material for ASG is affected by the required intrinsic characteristics (i.e., degradability) as well as technical characteristics (i.e., tensile strength). Moreover, the ASG material should ideally integrate into the natural environment without any harmful consequences. Thus, introducing persistent plastics into marine environments has to be seen critically, and biodegradable materials should be considered for the construction of ASG. Apart from reducing the source of contamination, using a biodegradable material also prevents the disturbance of newly established seagrass because the structure does not need to be removed after the natural seagrass has re-established. The biodegradable ASG can be made of several potential materials, such as natural fibers, biodegradable plastic or a combination of both, depending on how long the artificial structure is needed. Pure cellulosic fibers, in the form of woven fabrics or filaments, degrade very fast: for cotton and linen fabric, a degradation time of 3–10 weeks was recorded (Dorée, 1920). Some compostable plastics, such as Polyhydroxyalkanoate (PHA), Polyhydroxybutyrate-valerate (PHBV) and Polycaprolactone (PCL), have been shown to degrade under marine conditions (Narancic et al., 2018). The material being used for restoration purposes needs to be thoroughly tested beforehand under the conditions prevailing at the restoration site to assure that it does not harm the environment. We suggest tests investigating degradability under marine conditions are carried out at different temperatures and at three levels (flask, aquaria, field), including ecotoxicity-tests. While the flask-test is important to prove and evaluate the mineralization of the material to CO_2, the two other levels serve to test under more realistic conditions and to analyze mechanical changes during degradation.

The ASG patch should be large enough to provide the shelter needed against hydrodynamic energy and erosion, but small enough to (a) be economically feasible; (b) not greatly disturb the natural environment (e.g., covering other habitats and reducing nutrient exchange between adjacent areas); and (c) provide enough space and light for seagrass to establish, grow and expand within and beyond the ASG boundaries. The dimensions of the ASG providing this facilitation can be explored in physical experiments in a hydraulic laboratory facility (e.g., a wave flume or basin) with systematic variation of specific parameters (e.g., wave height/length, distance between mats) (Paul and Gillis, 2015; Villanueva et al., 2021). The prototype meadow can vary in canopy height, leaf density and meadow length as well as geometry and mechanical properties of individual stems, in order to control sedimentation and reduction of hydrodynamic energy (e.g., Taphorn et al., 2021). When dimensioning an ASG mat to support seagrass restoration, it is important to consider that a trade-off appears when modifying the flow field by an artificial structure since every structure exposed to flowing water will lead to both scouring (i.e., erosion) and deposition (i.e., burial) processes. Furthermore, it is important to carefully consider the role of stem density, as light availability plays a major role on seagrass survival (van der Heide et al., 2011; Adams et al., 2016).

The spatial configuration of the ASG mats should consider the location of the re-establishing natural seagrass relative to the position of the ASG (i.e., the envisaged area for natural restoration) and provide an effective spacing in the design. Potential arrangements include an integrated approach, where seagrass restoration takes place inside the ASG mats. However, a possible shortcoming could be the shading of the areas for seagrass recovery by the ASG (Hengst et al., 2010). The ASG meadow can also give shelter to adjacent areas where the seagrass recovery is supposed to take place. Therefore, for sites that are mainly exposed to intertidal currents or unidirectional wave action, a stripe-like design could fulfill the task of sheltering the restoration areas without shading upcoming natural seagrass, whereas more complex hydrodynamic conditions could require a checkerboard-like configuration.

Restoration efforts were generally more successful when using some kind of anchoring (van Katwijk et al., 2016), which keeps the transplanted natural seagrass in place. The ASG method is supposed to reduce the hydrodynamic energy at the bottom and could thus reduce the anchoring efforts. We recommend that special attention is paid when designing the base-layer of an ASG system. A grid-like structure for example permits water to flow through and thus requires less anchoring than a closed structure. Studies accompanying seagrass restoration should investigate the anchoring forces (in relation to flow velocity) in order to be able to design appropriate anchors.

Performance Tests

We recommend that once a prototype has been developed, it should be tested in a laboratory flume to evaluate if it provides the sheltering capacity needed at the restoration site. Measurements should comprise wave and current attenuation, sedimentation/erosion rate and light intensity inside the ASG. We encourage the realization of pilot projects in the field for the establishment of improved restoration guidelines before large-scale application in a restoration attempt to account for the highly diverse natural impacts, which cannot be tested under laboratory conditions (e.g., impact of microbial growth, sunlight, grazing, varying turbidity, etc.).

CONCLUSION

Artificial seagrass (ASG) provides promising benefits for seagrass restoration by creating suitable hydrodynamic and light conditions as well as sediment stabilization for seagrass establishment when habitat conditions are too harsh for seagrass meadows to re-establish themselves. While the general facilitating effect of ASG has been proven in laboratory studies, past field applications have been limited to small-scale patches. To effectively test the potential of ASG in habitat restoration, large-scale field trials are required to minimize the negative effects induced by small plot sizes. We suggest that ASG should only be applied if hydrodynamic energy is too high for natural recolonization and if it is impossible to introduce natural protection structures at the selected restoration site. If applied, we recommend the use of ASG only to create a self-supporting and self-maintaining ecosystem. To facilitate the application of ASG for restoration purposes, we propose to use an ASG produced from biodegradable materials. We encourage more studies, which are urgently needed to overcome the uncertainties associated with this promising approach.

AUTHOR CONTRIBUTIONS

JC, CA, MT, and RV developed the structure and content. JC took the lead in writing the manuscript. All authors conceived the original idea and discussed the contents and contributed to the final manuscript.

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